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Three Point Bending of Laser Engineered Net Shaping (LENS) Repaired Inconel 625 †

Izabela Barwinska [1,2,*], Mateusz Kopec [1,3], Magdalena Łazińska [2], Adam Brodecki [1], Tomasz Durejko [2] and Zbigniew L. Kowalewski [1]

1 Institute of Fundamental Technological Research, Polish Academy of Sciences, Pawinskiego 5B, 02-106 Warsaw, Poland; mkopec@ippt.pan.pl or m.kopec16@imperial.ac.uk (M.K.); abrodec@ippt.pan.pl (A.B.); zkowalew@ippt.pan.pl (Z.L.K.)
2 Faculty of Advanced Technologies and Chemistry, Military University of Technology, Sylwestra Kaliskiego 2, 00-908 Warsaw, Poland; magdalena.lazinska@wat.edu.pl (M.Ł.); tomasz.durejko@wat.edu.pl (T.D.)
3 Department of Mechanical Engineering, Imperial College London, London SW7 2AZ, UK
* Correspondence: ibarw@ippt.pan.pl
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Abstract: In this paper, the LENS technique with optimized parameters was applied to investigate the feasibility of Inconel 625 repair process. The process was performed on the substrate material heated to 300 °C at laser power of 550 W. Subsequently, the specimens were subjected to microhardness and three-point bending tests to assess the effectiveness of the repair system. The results showed that the mechanical properties of the Inconel 625 specimens repaired by using the LENS system were similar or even better than those of the substrate material.

Keywords: LENS technology; Inconel alloys; repair process; additive manufacturing

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1. Introduction

Inconel 625 is a nickel-based alloy which is used for applications in the aircraft engine industry due to its outstanding high-temperature strength properties, excellent corrosion resistance, and weldability [1,2]. Apart from its widespread applications in the aerospace sector, it is also being used in marine engineering, chemical processing, pollution-control equipment, and in nuclear reactors. It should be noted that the excellent mechanical properties of Inconel 625 are mainly related to its multicomponent alloying with elements such as carbon, chromium, molybdenum, and niobium. Additionally, Inconel 625 is characterized by the ability to dissolve high concentrations of alloying elements, which further enables its solid-solution strengthening. However, due to its complex composition, Inconel 625 is difficult to process due to its segregation of alloying elements and, related to such phenomenon, its uneven stress distribution [2–5].

Aircraft components are exposed to local impacts, corrosion, fatigue, and thermal cycles which could limit the service life of aircraft significantly. In order to prevent parts being discarded as scrap after failure, certain non-destructive methods are used to detect defects in its macrostructure. Subsequently, depending on the damage type, the part can be subjected to a dedicated repair process [6]. Repair of damaged parts or insufficiently designed components is necessary to prolong their lifetime. Moreover, it is economically beneficial, reducing costs by avoiding the manufacturing of a new component. The repair processes are often performed to restore the object dimensionally and to improve its fatigue resistance, crack patching, and enhance its anticorrosion resistance [7]. The repair processes can be performed by using a number of welding processes, for example: different variations of gas tungsten arc (GTAW) welding [8], friction welding (FW) [9], cold metal transfer (CMT) welding [10], and metal inert gas (MIG) welding [11]. However, these conventional methods promote segregation of the brittle phases and simultaneous grain growth leading, consequently, to microfissuring [12]. Benoit et al. [13] compared cold metal transfer and MIG welding process for the welding of Inconel 718. The results showed, that the processed alloy exhibited improved properties when the CMT method was applied. It should be noted, that the CMT method introduce a lower residual stress level and narrower width of the heat affected zone could be obtained as compared to MIG welding method. However, despite the better weldability, the welded Inconel 718 alloy was still enriched with brittle phases. One should highlight, that conventional repair methods have a number of disadvantages, particularly during the repair of complex-shaped parts made of multicomponent alloys.

A new generation of repair processes promises to deposit coatings consisting of mixtures of powders, even with high entropy, which could protect the substrate material against high temperature and could also improve the mechanical properties of repaired elements [14]. One of the promising laser repair methods is laser engineered net shaping technology (LENS). LENS is an additive manufacture technique which enables a manufacturing of the three-dimensional objects using the layer-by-layer build process. During the LENS repair process, the powder is injected into a high-vacuum chamber together with an inert gas through a nozzle. A focused laser beam forms a pool on the surface of the substrate material and melt the feeded powder, resulting in the stable connection of materials. The advantage of the LENS system over conventional methods is primarily the narrow heat-affected zone formed due to a high-energy laser beam for cladding, which is concentrated in a relatively small area and therefore does not cause overheating of the workpiece [15,16].

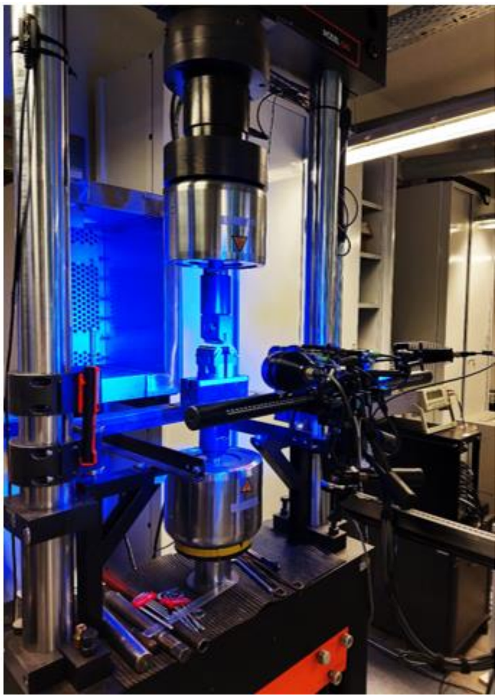
Nickel-based alloys, characterized by excellent mechanical properties and high corrosion resistance, tend to segregate brittle phases during long-time high-temperature exposure [17]. In addition, the high manufacturing cost of these alloys [18] makes it important to repair damaged parts without replacing them. Therefore, this article examines the effectiveness of LENS repair process for Inconel 625 alloy through the basic mechanical tests including three-point bending and hardness measurements.

2. Materials and Methods

In this study, the LENS 850-R system (Optomec, Albuquerque, NM, USA) was used to repair model specimens made of the Inconel 625 alloy (Figure 1a). In the first stage of experiment, square shaped pockets of 1 mm depth and 5 mm width were machined in a substrate material using a CNC machine. Then, using the optimized parameters of the LENS system (Table 1), the model specimens were repaired with the Inconel 625 powder of the chemical composition shown in Table 2.

The micro-hardness measurements of cladding, heat affected zone, and substrate material were determined using a ZWICK hardness tester (Materialprüfung, Ulm, Germany). They were conducted along the deposition direction with 0.1 mm increments, starting from the edge of the cladding up to its core and repeated in five different cross-sections of the repaired specimen. Three-point bending tests were performed at room temperature to compare the mechanical responses depending on the material state of the repaired model specimens and substrate material. Tests were carried out on a servo-hydraulic Instron 1343 testing machine (Instron, Norwood, MA, USA), under displacement control for constant strain rate of 2×10^{-3} s^{-1}. In this research, three rectangular specimens of $70 \times 5 \times 5$ mm were tested per each condition to calculate the average values and standard deviations of the flexural strength. In order to investigate the strain distribution, each bending test was monitored using Digital Image Correlation (DIC) system—Aramis 12M (GOM mbH, Braunschweig, Germany). A general view of the experimental setup was presented in Figure 1b. The system was equipped with lenses of a total focal length equal to 75 mm and calibration settings appropriate to the measuring area of 170×156 mm. Before testing, the system was calibrated using a certified GOM calibration plate. The specimens' structures after the bending tests were observed using Jeol J0L6360 LA scanning electron microscopy.

(a)



(b)

Figure 1. (**a**) General view of the laser engineered net shaping system; (**b**) experimental setup for three-point bending supported by DIC system.

Table 1. The optimized LENS process parameters.

Laser Power [W]	Feed Rate [mm/s]	Powder Flow Rate [g/min]	Laser On/Off Wait [ms]	Substrate Temperature [°C]
550	12	15	400	300

Table 2. Chemical composition of the Inconel 625 powder.

Element	O	Fe	Ni	Al	Si	Zr	Nb	Mo	Cr	Mn
% wt.	2.18	5.10	55.87	0.38	0.34	0.48	3.83	9.03	22.53	0.27

3. Results and Discussion

3.1. Three-Point Bending Tests

In order to assess the effectiveness of the LENS system during repair of the Inconel 625 specimens, three-point bending tests were performed. The tests were carried out for two types of material: the first one with LENS cladding, and the second with a substrate material. It was observed that the deposited LENS cladded specimens were characterized by slightly higher bending strength (Figure 2). The difference in the mechanical response between both materials in question was approx. 60 MPa. It should be mentioned, that regardless type of specimens, the strain distribution monitored by DIC system during the tests, was similar (Figure 3). In order to assess the quality of the deposited clad after bending, specimens' sidewalls were polished prior to the test. Microscopic observations did not reveal any surface cracks for both groups of specimens. Additionally, no pores and cracks between the substrate and deposited material were observed for repaired specimen. However, it should be mentioned, that the deformation covered either the deposited zone or the subsequent cladded layers. The mechanical response of the Inconel 625 alloy in its different states resulted from the initial microstructures of these states. The repaired alloy was characterized by a columnar structure in the laser cladding zone while the substrate material remained uniform throughout.

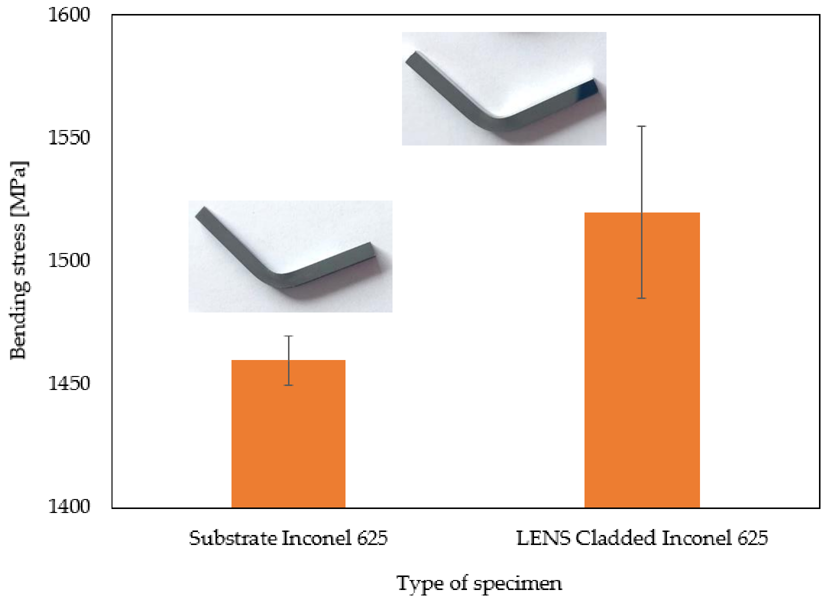


Figure 2. Comparison of the bending strength for the substrate Inconel 625 and LENS cladded Inconel 625.

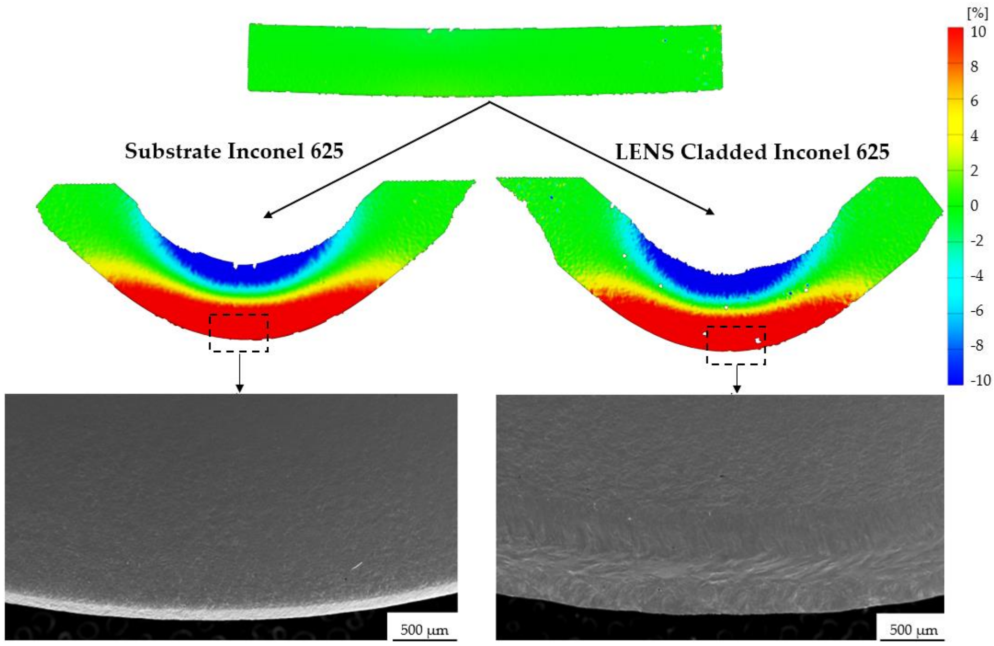


Figure 3. DIC strain distribution maps of both materials tested, and structural images of their surfaces after bending tests.

Similar results were reported by Wei et al. [18], who investigated the mechanical properties of the repaired Inconel 625 by using the LAM system (LAM, LSF-12000, Nanjing, China). The repair process consisted of filling the pre-machined defects in the substrate. In this work, a combination of the following parameters was selected: laser power of 1.4 kW, scanning speed of 400 mm/min, powder feed rate of 6 g/min, and the laser spot diameter of 3 mm. Such process parameters enabled the authors to obtain a similar hardness and tensile strength for the repaired specimens and those of the as-received material. Dudkiewicz et al. [1] reported, that specimens of the Inconel 625 alloy produced using LENS were characterized by higher mechanical properties than those deposited by means of the high-power CO_2 laser. In the investigations reported, the specimens fabricated using both methods (gauge length of 20 mm and a diameter of 5 mm) were subjected to tensile tests. The first deposition method used LENS MR 7 (Optomec, Albuquerque, NM, USA) with the following parameters: laser power of 400 W, laser spot diameter of 1.2 mm, working table feed rate of 600 mm/min, powder flow rate of 15 g/min. The second method applied CO_2 high power laser with the Trumpf machine Lasercell 1005 (Trumpf GmbH, Ditzingen, Germany,) using a laser power of 2.275 kW, laser spot diameter of 2.0 mm, scanning speed of 800 mm/min, and powder feed of 15 g/min. min. The results showed that the deposition of Inconel 625 by means of the LENS system led to the higher values of the yield point and tensile strength of about 10% and 8%, respectively.

3.2. Microhardness Profile

The hardness distribution of the repaired model specimen was measured in the cross section from the top surface to the base metal (Figure 4). The maximum hardness value equal to 269 HV0.1 was observed in the laser cladding zone, and it decreased with increasing distance from the edge of the laser cladding. However, the hardness of the substrate material after deposition remained at the constant level, as that for the as-received material (i.e., approx. 249 HV0.1). It should be mentioned that no significant deviations were observed in the heat-affected zone, since the hardness was kept within the range from 251 to 253 HV0.1.

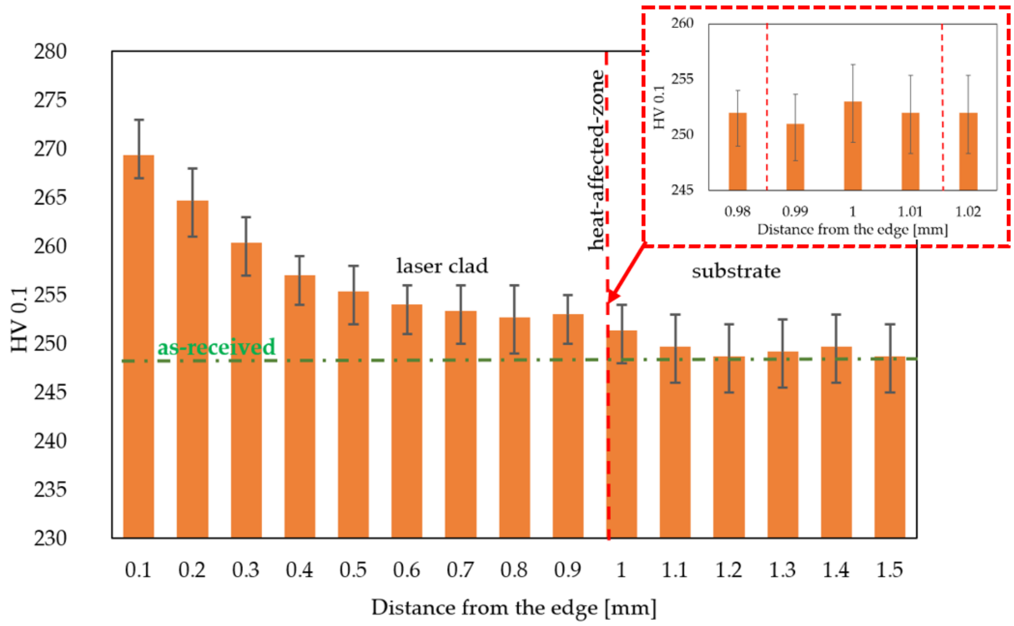


Figure 4. Hardness measurements of the repaired Inconel 625 alloy specimens.

Similar observations of the microhardness were reported by Abioye et al. [17], who used fiber laser (IPG photonics) to deposit a corrosion protection layer of the Inconel 625 wire on the same base material. It was found that the cladding applied by using laser welding exhibited a higher hardness value than the substrate material. Moreover, the hardness of substrate material did not increase significantly after the process. On the other hand, Dudkiewicz et al. [1], thanks to the comparison of two additive manufacturing methods (LENS technique and high power CO_2 laser), concluded that the LENS system enabled to increase the microhardness of the deposited Inconel 625 which was mainly related to the higher cooling rate occurring as a result of this method.

4. Conclusions

The mechanical properties of the repaired Inconel 625 by means of the LENS process with optimized parameters were compared to those determined for the as-received material. The results indicated that the LENS system can improve the strength of the material significantly. In comparison to the substrate material, the repaired specimens exhibited both increased microhardness of the modified surface and slightly higher bending strength. Moreover, the LENS process ensured a proper adhesion between the materials, since no any discontinuities were observed after bending tests.

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